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Author: Aneta Spyra, Natalia Jędraszewska, Małgorzata Strzelec, Mariola Krodkiewska

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Further expansion of the invasive mussel *Sinanodonta woodiana* (Lea, 1834) in Poland – establishment of a new locality and population features

Aneta Spyra*, Natalia Jędraszewska, Małgorzata Strzelec and Mariola Krodkiewska

Department of Hydrobiology, Faculty of Biology & Environmental Protection, University of Silesia, Bankowa 9, 40-007 Katowice, Poland

Abstract – The increasingly frequent appearance of invasive species of mussels is a common phenomenon nowadays. Their rapid expansion is a significant component of the global changes that pose a great ecological impact and a serious threat to the diversity of native fauna. This study documents new localities of occurrence of *Sinanodonta woodiana* in Poland. We also attempted to determine its density, biomass, morphometric features and age structure. We found that its presence is clearly related to temperature and that the current range of its occurrence in Poland mostly overlaps with the areas with the highest average annual temperatures. The study showed significant differences in mean density between the fishponds: on particular sites the density amounted to 9 individuals/m^2 and their biomass exceeded 3000 g/m^2. ANOVA revealed significant differences in the mean dimensions of the shells between the three fishponds related to their height and width. Seven-year-old individuals were the most numerous while one-, two-, five- and six-year-old specimens were the most numerous in pond 2. In our opinion, *S. woodiana* has created a permanent population that is probably able to breed. This is confirmed by the appearance of one-year-old individuals as well as the other younger age classes.

Keywords: invasive species / *S. woodiana* / new records / mussel

Résumé – L'expansion de la moule invasive *Sinanodonta woodiana* (Lea, 1834) en Pologne – nouvelles localisations et structure de population. L'apparition de plus en plus fréquente d'espèces envahissantes de moules est un phénomène fréquent. Leur rapide expansion est une composante importante des changements globaux qui causent un fort impact écologique et une grave menace pour la diversité de la faune indigène. Cette étude documente de nouvelles localités d'implantation de *Sinanodonta woodiana* en Pologne. Nous avons également tenté de déterminer la densité, la biomasse, les caractéristiques morphométriques et la structure d'âge. Nous avons constaté que sa présence est clairement liée à la température et que la gamme actuelle de sa localisation en Pologne recouvre principalement les zones où les températures annuelles moyennes sont les plus élevées. L'étude a montré des différences significatives de la densité moyenne entre les étangs : sur des sites particuliers, la densité est élevée à 9 individus/m^2 et la biomasse a dépassé 3000 g/m^2. L'ANOVA a révélé des différences significatives dans les dimensions moyennes de hauteur et largeur des coquilles entre trois étangs. Des individus de sept ans étaient les plus nombreux en 1 alors que les spécimens de un, deux, cinq et six ans étaient les plus nombreux dans l'étang 2. À notre avis, *S. woodiana* a créé une population permanente qui est probablement en mesure de se reproduire. Ceci est confirmé par l'apparition d'individus âgés d'un an ainsi que la présence d'autres classes d'âge jeunes.

Mots-clés : espèce envahissante / *S. woodiana* / moule

1 Introduction

Various types of human activity have permitted the intentional or accidental dispersion of species outside of their native ranges (Kolar and Lodge, 2001). Some of them have become invasive species (Williamson and Fitter, 1996) that change the structure and functioning of the ecosystem that they occupy (Sakai *et al.*, 2001; Simon and Townset, 2003), thus causing serious economic damage (Strayer *et al.*, 2006; Strong *et al.*, 2008) and, in some cases, threats to the health of humans and domesticated animals (Gilioli *et al.*, 2014).

* Corresponding author: aneta.spyra@us.edu.pl

Table 1. The role and use of *S. woodiana* in native and alien range.

Role in freshwater ecosystems	Present and future use
1. Accumulation of heavy metals in bodies and shells (Cr, Mn, Fe, Cu, Ni, As, Zn, Se, Ag, Mo, Cd, Pd) and contaminations *e.g.* pesticides (Uno *et al.*, 2001; Królak and Zdanowski, 2001; Liu *et al.,* 2010; Zhang *et al.*, 2014; Yancheva *et al.,* 2016) and nutrients (Sinicyna *et al.*, 1997; Królak and Zdanowski, 2007) 2. Filtration and therefore cleaning the water by reducing algae, particles and toxins in the water column (Kurnia *et al.*, 2010) 3. It constitutes a feeding base for: *Haematopus ostralegus*, *Haliaeetus albicilla*, *Sus scrofa*, *Vulpes vulpes* (Andrzejewski *et al.*, 2012) 4. Mussel deposits are a nutrient rich and easily assimilated food source (Howard and Cuffey, 2006) 5. Ecosystem engineers by physically altering its structure (Bódis *et al.*, 2014a) 6. Living mussels (Vaughn *et al.*, 2008) and empty shells are substrates and shelters for benthic organisms (Bódis *et al.*, 2014b)	1. In China as a traditional edible mussel (Chen *et al.*, 2012) 2. As a unique bioindicators (biomarker) in monitoring (Reichard *et al.*, 2012; Chen *et al.*, 2012; Li *et al.*, 2015) 3. As a toxic Microcystis-blooming controller, phytoplankton controller (Liu *et al.*, 2014) and for assessing the contamination of organotins (Yang *et al.*, 2008), organochlorines (Bian *et al.*, 2009) and heavy metals (Liu *et al.*, 2010) 4. In Tuscany it was introduced specifically for the production of artificial pearls (Berni *et al.*, 2004; Liu *et al.*, 2014) 5. Its liposome-incorporated aqueous extracts can potentially be applied as a natural antitumor and immunomodulator formulation (Liu *et al.*, 2008). It has been recorded as a mollusc medicine in the Dictionary of Chinese Traditional Medicine for the treatment of the diseases of modern civilisation, *e.g.* diabetes 6. It is sold in garden centres as a "biofilter" for garden ponds (Packet *et al.*, 2009) 7. It is used in monitoring genotoxicity (Woźnicki *et al.*, 2004; Kolarević *et al.*, 2011; Ciparis *et al.*, 2015)

Currently biological invasions are considered to be the biggest threats to global biodiversity, threats that are tantamount to the disappearance or fragmentation of natural habitats (Katsanevakis *et al.*, 2014; Koester and Gergs, 2014). Most of the invasions occur in environments that remain under the influence of human activities, especially disturbed habitats, as well as on sites that have been slightly disturbed by natural processes (Williamson, 1996; Havel *et al.*, 2005; Łabęcka and Domagała, 2016). In freshwater ecosystems, which are more susceptible to biological invasions, the appearance of alien species can be associated with the intensity of their use by humans for the production of food, trade, recreation or water transport (Dudgeon *et al.*, 2006; Sousa *et al.*, 2014).

In recent decades an increasing number of sites of alien freshwater mussels such as: *Dreissena polymorpha* (Pallas, 1771), *Dreissena bugensis* (Andrusov, 1897), *Corbicula fluminea* (O.F. Müller, 1774), *Corbicula fluminalis* (O.F. Müller, 1774), *Limnoperna fortune* (Dunker, 1857) and *Sinanodonta woodiana* (Lea, 1834) (Bódis *et al.*, 2014a,b) have been observed. Some of these *e.g.* the Chinese pond mussel, already have the status of invasive species (Bogan *et al.*, 2011; Douda *et al.*, 2012; Reichard *et al.*, 2012). Its native range includes China, Taiwan, Cambodia, Thailand, Japan, Indonesia and the Amur River basin (Tebe *et al.*, 1994; Watters, 1997; Popa *et al.*, 2007). Its huge expansion has provided a continuing increase in the number of habitats colonised over almost all of Europe (Cianfanelli *et al.*, 2007; Adam, 2010; Colomba *et al.*, 2013) including also Croatia (Lajtner and Crnčan, 2011) and Montenegro (Tomović *et al.*, 2013). It has also appeared in other regions *e.g.* in North America (Bogan *et al.*, 2011), the Indonesian islands of Java and Sumatra, Central America, Costa Rica (Watters, 1997), the Philippines (Demayo *et al.*, 2012), and in the Asian part of Turkey (Ercan *et al.*, 2014). In most cases, its spread is associated with the development of commercial trade (primarily in East Asian cyprinid fish species) between different countries and regions. Fish are imported for breeding purposes as well as to control the aquatic vegetation in fish ponds (Paunović *et al.*, 2006; Minchin, 2007; Cappelletti *et al.*, 2009). The role of *S. woodiana* in ecosystems and its different potential uses are not without significance (Tab. 1). In Poland it is known as a food resource for different animals (Andrzejewski *et al.*, 2012), while the bioaccumulation of calcium, phosphorus and heavy metals in the soft tissues and shells of *S. woodiana* has also been observed (Królak and Zdanowski, 2001, 2007).

During an invasion of *S. woodiana* an important role is also played by its non-selective choice of host in its larval stage in comparison with the native Unionidae (Kiss, 1995; Blazek and Gelnar, 2006; Douda *et al.*, 2012; Popa *et al.*, 2015). This reduces the opportunities for survival for native mussels (Lydeard *et al.*, 2004; Corsi *et al.*, 2007; Cappelletti *et al.*, 2009; Hliwa *et al.*, 2015), which are considered to be one of the most threatened groups of organisms in the world (Vaughn *et al.*, 2008; Allen and Vaughn, 2011; Kamburska *et al.*, 2013). In comparison with the native Unionidae, its specific physiological conditions which are associated with the activity of the enzyme cholinesterase, allow it to tolerate a wide range of environmental factors (Corsi *et al.*, 2007) (Tab. 1). Therefore, in the area being colonised it occurs in aquatic environments that are rich in nutrients (Paunović *et al.*, 2006; Beran, 2008; Demayo *et al.*, 2012; Benko-Kiss *et al.*, 2013) and in those that have a low trophic status, *e.g.* in alpine lakes in Italy (Cappelletti *et al.*, 2009; Ciutti *et al.*, 2011; Kamburska *et al.*, 2013), in Austria (von Taurer, 2009) or in environments with disturbed temperature conditions due to the use of water in power plants (Kraszewski and Zdanowski, 2001).

In Poland, the first occurrence of *S. woodiana* was reported in the mid-1980s of the last century, in five Konin lakes that are connected by a system of canals, to which it was introduced along with fish from a Gosławice fish farm (Soroka and Zdanowski, 2001). By 2012, it was found inten localities (Andrzejewski *et al.*, 2013) and now it occurs in more than 20 localities. It primarily occurs in fishponds (Najberek *et al.*, 2011, 2013; Spyra *et al.*, 2012; Andrzejewski *et al.*, 2013), although it has also been observed in other types of aquatic environments on a few occasions (Beran, 2002; Andrzejewski *et al.*, 2012).

Habitats that have invasive species provide the opportunity to follow their ways and modes of dispersion and the ability to develop potential actions to prevent their spread. Therefore, the aims of our study were to: identify any new sites of occurrence of *S. woodiana* in Poland that are located in areas where the average annual air temperature exceeds +8° and to determine its density and biomass in the fishponds studied. We also performed a biometric analysis of its shells and determined the age structure of the populations studied in order to answer the question of whether the Chinese giant mussel has created permanent populations in the ponds studied.

2 Materials and methods

2.1 Study area

The study was carried out in 2014 in three fish ponds, located in the Vistula River valley, ponds which form part of the fish pond complex in Dębowiec (Southern Poland, Silesian Upland) (Figs. 1 and 2). This area is surrounded by forest. The ponds are supplied with water from the Vistula River (ponds 2 and 3) and its left-bank tributary the Knajka River (pond 1). The water from the ponds discharges into the Knajka River resulting in significant fluctuations in its water level. The fish ponds were created along the Knajka River in an area where extensive network of artificial drainage ditches had been created, in particular in the northern section. The fish ponds are characterised by a homogeneous muddy bottom sediments. They are small (from 11 to 17 ha) and shallow-the average depth ranged from 1.0 m in pond 3 to 1.5 m in pond 1 (Tab. 2).

The pond management in the area studied is mainly done through drying out the ponds, the application of calcium oxide, bottom dredging and dredging the bottom ditches (blowdown) (Tab. 2). Cyanophytal and algal blooms occur in the fishponds from late spring to early autumn. The ponds are stocked with different species of fish: *Cyprinus carpio*, *Ctenopharyngodon idella*, *Mylopharyngodon piceus* and others (Tab. 2).

2.2 Data collection, processing of the samples, biometrical and statistical analysis

Samples were taken from each pond immediately after the discharge of the water. Seven sampling areas (1 m^2) were randomly designated in each pond except for pond 1, in which the extreme wetness of the bottom sediments only allowed four sampling areas to be selected. A square frames which identified an area for sampling was placed on the bottom to a depth of 0.25 m and only live specimens were sampled. After thoroughly cleaning the shells, biometrical analyses were performed and the following biometric parameters were taken into consideration: total length (L), umbo/ventral shell edge height (H) and width (W). The measurements were taken to the nearest 0.1 mm using callipers. Evaluation of the morphological variation of mussels was carried out using the H/L and W/H coefficients. For the determination of mussel weight their shells were cleaned of bottom sediments and periphyton and were left to dry on a

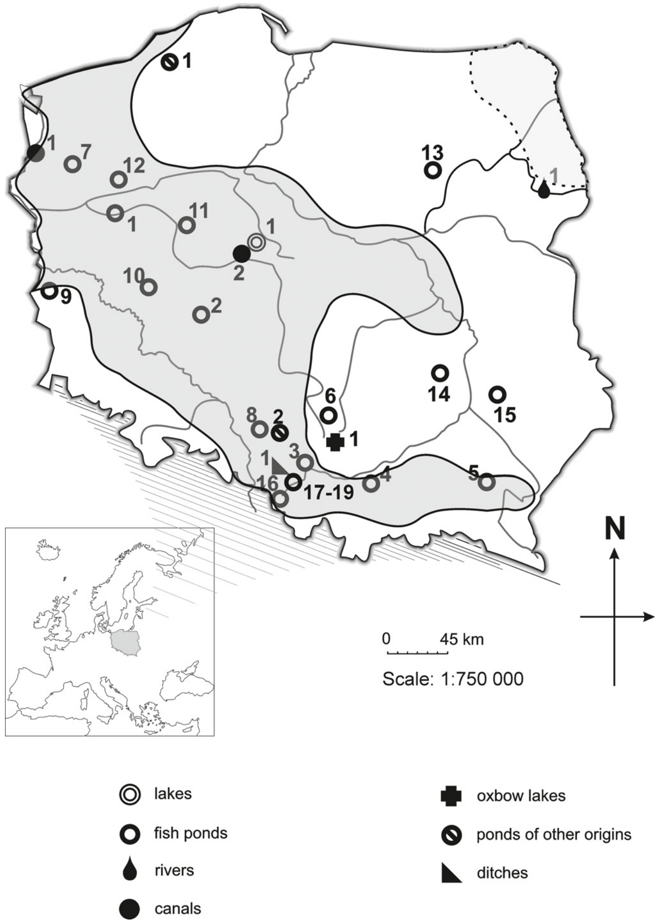

Fig. 1. Sites of *Sinanodonta woodiana* occurrence in Poland up to 2016 along with new localities in Dębowiec (ponds 17–19), borders of isotherms for the period 1971–2000 in Poland according to Lorenc (2005). — areas with the highest average annual temperatures; - - - areas with the lowest average annual temperatures; 1. Konin Heated Lakes System (Kraszewski and Zdanowski, 2001); 1. Fish ponds near Sieraków (Mizera and Urbańska, 2003); 2. Fish ponds near Milicz (Gąbka *et al.*, 2007); 3. Fish ponds in Góra and Goczałkowice (Spyra *et al.*, 2012); 4. Fish ponds in Spytkowice (Najberek *et al.*, 2011); 5. Fish ponds near Rzeszów (Wojton *et al.*, 2012); 6. Fish ponds Przeręb near Zator (Najberek *et al.*, 2013); 7–16. Fish ponds (Urbańska *et al.*, 2012): 7 – Zgliniec, 8 – Trzęsina, 9 – Urocze S rednie, 10 – Wojnowice, 11 – Wędkarski, 12 – Zydowski, 13 – Morys, 14 – Jedynka Nowy, 15 – Oko, 16 – Duży); 17–19: Fish ponds in Dębowiec : 17 – Łacki, 18 – Chłopski, 19 – Rajski (new sites); 1. Dolna Odra power plant canal (Domagała *et al.*, 2004); 2. Warta Gopło Canal (Kraszewski, unpublished); 1. Oxbow lake Krajskie (Zając *et al.*, 2013); 1. Water body in Czarny Młyn (Ożgo *et al.*, 2010); 2. Woodland pond in Piegza (unpublished data); 1. The Casprzyca Dith (Urbańska *et al.*, 2011); 1. The Narew River (Bőhme, 1998; Marzec, 2016).

blotting filter for 10 min before weighing. The body weight with the shell was determined to the nearest 0.5 g.

The basic criterion of shell length (L) was used in the assessment of the lifespan of mussels. The classification that linked the age of individuals with their size was determined according to Dudgeon and Morton (1983), from similar research that was conducted in a water body with undisturbed

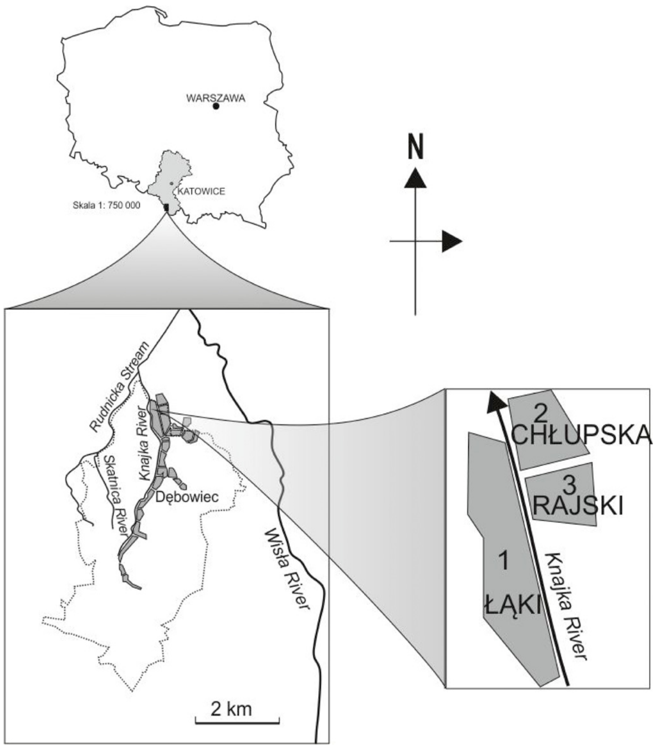

Fig. 2. Location of the study area and new sites of *S. woodiana* occurrence in Poland.

thermal conditions in the natural distribution range of *S. woodiana*. This method is known as a tool that gives the approximate age of mussels, which may have a different growth rate and maximum size in the areas colonised. The annual growth rings on the mussel shells had developed differently, which could lead to estimation errors. According to Neves and Moyer (1988) and Kiss (1995), the rings visible on the shell surface are of limited use for estimating the age of unionids and may not faithfully represent the actual age of the Chinese mussel in the case of unfavourable environmental conditions. We assumed that individuals with a shell length from 35 to 40 mm – were 1-year old, 68–80 mm – 2 years, 70–95 mm – 3 years, 85–100 mm – 4 years, 95–115 mm – 5 years, 110–120 mm – 6 years, 120–130 mm – 7 years and 162.5 mm – 8 years-old. Additionally we grouped the mussel shells into four size categories according to Afanasjev *et al.* (2001): young (up to 5 cm), small (to 10 cm), medium (10–15 cm) and large (above 15 cm).

The results obtained were analysed statistically using the "Statistica for Windows" version 12.0 program. The value of the morphometric variables and density did not reveal a normal distribution according to the Lilliefors test of normality (STATISTICA ver. 12.0) and this justified the use of non-parametric statistics. The significance of the differences between the various shell dimensions and the biomass of the individuals that were collected from the fishponds was evaluated using a rank-based nonparametric ANOVA, Kruskal–Wallis and multiple comparisons tests. Spearman rank correlation coefficients (r_s) were used to analyse the relationships between the average annual temperatures in localities in which *S. woodiana* was found in Poland (Data according to: Dekadowy Biuletyn Agrometeorologiczny, 2001–2002; Lorenc, 2005) and the number of sites where *S. woodiana* occurs.

3 Results

3.1 New sites of occurrence of *S. woodiana* in Poland

New sites where *S. woodiana* occurs in Poland were identified in the three fish ponds in Dębowiec (Fig. 2). The water bodies in which the presence of *S. woodiana* was confirmed are small and very shallow which means that the water temperature must depend strongly on the air temperature. We found that the occurrence of this species is clearly related to temperature and that the current range of its occurrence in Poland mostly overlaps with those areas with the highest average annual temperatures (according to the data of Lorenc (2005) from 1971 to 2000). Figure 1 not only presents the areas of occurrence of *S. woodiana* that existed in Poland up to 2016, but also the borders of the isotherms of the highest and lowest average annual temperatures. Analysis of Spearman rank correlation coefficients (r_s) showed a significant positive correlation between the average annual temperatures and the number of sites where *S. woodiana* occurred ($r_s = 0.901$, $p < 0.05$). *S. woodiana* was the only species of bivalve found in the fishponds studied.

As is clear from Table 1, the *S. woodiana* mussel can be the substratum for other animals. We found numerous empty shells in the shore zone of ponds and we also observed that a lot of them were the substratum for benthic invertebrates.

3.2 Density and biometric parameters of *S. woodiana* populations

Fifty-five live specimens of *S. woodiana* were collected from the Dębowiec fishponds. The highest density values were indicated in pond 1 (9 ind./m^2) (Tab. 3). The study showed statistically significant differences in mean density between the fishponds. It was significantly smaller in ponds 3 (543 ind./m^2) than in the other ponds (ANOVA: *H* (2; $N = 18$) = 7.141652, $p = 0.0281$, post-hoc $p < 0.05$).

Mussels were present at each of the selected study sites in ponds 2 and 3 and but only on four sites in pond 1. Their density amounted to 9 ind./m^2 in pond 1, while their density in pond 3 was 1 or 2 ind./m^2 and their biomass occasionally exceeded 3000 g/m^2 (pond 1, site 1) (Tab. 3).

Morphometric analysis of the shells showed that the highest average length, height, width and height (*H*) to length (*L*) ratio were recorded for the specimens collected from pond 3 and the smallest average values were found for the specimens from pond 2 (Tab. 4). The maximum and minimum values of the parameters analysed were identified for the individuals collected from pond 2. One-way ANOVA revealed significant differences between the three fishponds in the mean dimensions of *S. woodiana* specimens that were related to their height and width (ANOVA: *H* (df 2, $N = 55$) = 7.220472, $p = 0.270$, width (ANOVA: *H* (df 2, $N = 55$) = 14.21951, $p = 0.0008$). These parameters were statistically larger in the mussels collected from pond 3 in comparison to ponds 1 and 2. The ANOVA showed no differences between the ratios of *H*/*L* and *W*/*H* of the shells collected from each pond (Tab. 5). The

Table 2. Environmental characteristic of the fish ponds in Dębowiec – management and stocking practice.

	Pond 1 (Łąki)	Pond 2 (Chłupska)	Pond 3 (Rajski)
Area	17 ha	13 ha	11 ha
Sources of water supply	Rivers Vistula and Knajka	Vistula River	Vistula River
Mean depth	1.5	1.2	1.0
Bottom sediments	mud		
Pond management	Pond drying, application of calcium oxide, periodic dredging the bottom of ditches (blowdown), feeding the fish with a mixture of grains (triticale)		
Length of drying periods	From one day to five months		
Cyanophytal and algalblooms	Periodic blooms: from late spring to early autumn, that disappear spontaneously		
Fish stocking	*Cyprinus carpio* L – from its own fish farm *Mylopharyngodon piceus*, *Ctenopharyngodon idella*, *Hypophthalmichthys molitrix*, *Leuciscus idus*, *Silurus glanis*, *Abramis brama*, *Carassius carassius*, *Esox lucius*, *Rutilus rutilus*, *Perca fluviatilis*, *Gymnocephalus cernua* – are acquired from other fish farms		
Plants	Fish feeding prevents the overgrowing of the ponds Shores are covered with *Phragmites australis*		

Table 3. Biomass [g] and density [ind./m^2] of *Sinanodonta woodiana* in the Dębowiec fish ponds.

No of sampling site	Pond 1		Pond 2		Pond 3	
	Biomass	Density	Biomass	Density	Biomass	Density
1	3307	5	1838	4	124.5	1
2	432	1	2104.5	5	379	1
3	1885.5	3	1634	4	521	1
4	2951.5	9	869	2	904	2
5	–	–	1493	4	652	2
6	–	–	2173.5	8	376	1
7	–	–	1409	1	427	1
Mean	**1869.5**	**4.5**	**1448.6**	**4**	**543.2**	**1.3**

greatest values of both indices were recorded for the specimens collected from pond 3.

The larger average biomass (g/m^2) was found for specimens that were collected from pond 1 and the smallest for those that were found in pond 3 (Tab. 3). The specimens with the largest weight were collected in ponds 1 and 2, whereas in pond 3, the smallest were recorded (Tab. 4). However, one-way ANOVA showed no significant differences in the average weight of the mussels between the specimens collected from the three fishponds (ANOVA: H (df 2, $N = 55$) = 0.6495031, $p = 0.7227$) (Tab. 5).

The detailed analysis of the morphological variation of mussels, considering only the individuals from age classes that occur in each pond – (7 and 8-year-old specimens) showed no statistically significant differences in all of the analysed parameters (ANOVA: H (df 2, $N = 51$) = 0.70313, $p = 0.7036$).

3.3 Age structure of *S. woodiana* populations in fishponds

The most numerous individuals in fish ponds 1 and 2 were seven-year old (large) (Tab. 6). One-year-old (young), two-year-old (small), and five- and six-year-old specimens (medium) also occurred in pond 2 but they were not found in the other ponds. Eight-year-old mussels (large) were the most numerous in pond 3. The appearance of one-year-old (young) individuals and the other young age classes shows that population of *S. woodiana* in pond 2 can be supposed to be able to breed. The fact that the young and small specimens were only found in pond 2 probably does not mean that they were absent in ponds 1 and 3 and this implies that this species is presumably able to create permanent populations in those ponds too that are also able to breed. Although we selected 7

Table 4. The morphometry of *Sinanodonta woodiana* shells in Dębowiec fish ponds, *n* – number of specimens.

Pond	Mean	*n*	SD	Minimum	Maximum
Length					
1	156.3	18	23.7	121.7	200
2	149.9	28	33.9	42.5	204.6
3	179.3	9	33.9	132.4	213.8
Height					
1	110.0	18	18.8	85.5	153.6
2	102.5	28	24	30.9	158.5
3	127.1	9	20.6	90.2	156.4
Width					
1	60.8	18	10.1	49.4	86.3
2	53.2	28	14.0	13.3	97.8
3	69.7	9	9.7	48.6	86.1
H/*L*					
1	0.7027	18	0.040	0.614	0.7818
2	0.6858	28	0.0449	0.5238	0.7746
3	0.7101	9	0.1377	0.6693	0.790
W/*H*					
1	0.555	18	0.0388	0.4927	0.64568
2	0.5175	28	0.050	0.430	0.6338
3	0.550	9	0.500	0.4817	0.620
Weight (g)					
1	476.4	18	275.9	192.5	1350.0
2	411.1	28	246.3	8.0	1409.0
3	376.5	9	124.4	124.5	521.0

Table 5. The results of the ANOVA Kruskal–Wallis for the morphometry of the *Sinanodonta woodiana* shells.

Variables	Kruskal–Wallis ANOVA
Weight (g)	H (df 2, $N = 55$) = 0.6495, $p = 0.7227$
Total length (L) (mm)	H (df 2, $N = 55$) = 0.8518, $p = 0.6532$
Height (H) (mm)	H (df 2, $N = 55$) = 7.2204, $p = 0.0270$
Width (W) (mm)	H (df 2, $N = 55$) = 14.2195, $p = 0.008$
W/H (mm)	H (df 2, $N = 55$) = 9.3891, $p = 0.091$
H/L (mm)	H (df 2, $N = 55$) = 3.85872, $p = 0.1452$

sampling areas of 1 m^2 in each pond, we found only 9 specimens in pond 3. Numerous empty shells had accumulated around the island of fishpond 2 and in the shore zone of other ponds, proving that the Chinese mussel had previously been present in large numbers in this pond.

4 Discussion

4.1 New sites of occurrence of *S. woodiana* in Poland

The appearance of alien species of bivalves in freshwater ecosystems that are particularly vulnerable to invasions (Sala *et al.*, 2000) is now becoming a common phenomenon (Popa *et al.*, 2011). Alien species are often able to settle permanently and survive in highly disturbed ecosystems (Cross *et al.*, 2010) which also include fish ponds that are more tolerant to environmental stress, one of the determinants of the invasion's success (Bielen *et al.*, 2016). This study documents three new localities of *S. woodiana* populations in fishponds that belong to the Dębowiec fish farm in Poland.

S. woodiana is known to be a species that is able to survive winters when the water temperature drops below 0 °C (Domagała *et al.*, 2007; Lajtner and Crnčan, 2011; Łabęcka and Domagała, 2016). This fact negates the thesis that exotic species cannot spread outside areas with fluctuating water temperatures and thus become a threat to native diversity (Najberek *et al.*, 2013). The climatic conditions in southern Poland may influence the current number of sites where Chinese mussels occur. It is possible that the tolerance of *S. woodiana* to low temperatures and its ability to quickly adapt to changing increases the opportunities for it to colonise new habitats (Douda *et al.*, 2012). Despite this fact, we found that its range in Poland is clearly related to areas that have the highest average annual temperature isotherms (18 of the 26 sites where *S. woodiana* occur), and this was supported by the results of statistical analysis. In Poland its occurrence outside the borders of the highest annual temperatures was recorded at

Table 6. Age structure (%) of the *Sinanodonta woodiana* populations in the Dębowiec fish ponds.

Age (years)	Pond 1	Pond 2	Pond 3	Total population
1	–	3.6	–	1.8
2	–	3.6	–	1.8
3	–	–	–	–
4	–	–	–	–
5	–	3.6	–	1.8
6	–	3.6	–	1.8
7	61.1	50.0	22.2	49.1
8	38.8	35.7	77.8	43.6
Number of specimens	**18**	**28**	**9**	**55**

8 sites. Only one of them is located close to the isotherm of the lowest annual temperature in the Narew River (Bőhme, 1998; Marzec, 2016).

Fish ponds are unevenly distributed in Poland. Central and southern Poland have the greatest number of ponds. According to Bukacińska *et al.* (1995), there are three basic localities of ponds in Poland: south-western, southern and south-eastern Poland, although *S. woodiana* also inhabits ponds located outside of this area. From our observations and the analysis of the occurrence of *S. woodiana* in Poland to date, it is possible to conclude that there is a clear tendency for this species to occur in areas that have the highest average annual temperatures. This fact indicates that its future occurrence will not depend on the number of existing and newly created fishponds unless they are located in those areas with the highest temperatures.

Freshwater mussels have a huge impact on the abiotic environment by physically altering the processes and structure of ecosystems (Bódis *et al.*, 2014a,b; Sicuro, 2015) as well as affecting the nutrient dynamics through the excretion and biodeposition of faeces and pseudofaeces and the bioturbation of the bottom sediments (Schmidlin *et al.*, 2012; Zieritz *et al.*, 2012; Sousa *et al.*, 2014). This can result in changes at numerous trophic levels (Pou-Rovira *et al.*, 2009) and cause a serious threat to biodiversity (Kovarik, 2003; Karatayev *et al.*, 2007; Simberloff *et al.*, 2013) including the globally threatened native Unionids due to degradation of their habitat (Vaughn and Hakenkamp, 2001; Lopes-Lima *et al.*, 2014). No native *Unionids* were found in the fishponds studied although in the opinion of the owner of the fish farm in Dębowiec, they had previously occurred in large numbers. Although the negative impact on native mussels, which is especially visible in areas where the density of Chinese mussels is high (Bódis *et al.*, 2014a,b), was described in the Konin lakes in Poland (Kraszewski and Zdanowski, 2007) as well as in other European countries (Cappelletti *et al.*, 2009; Munjiu, 2011; Benko-Kiss *et al.*, 2013; Kamburska *et al.*, 2013) the coexistence of native Unionids with *S. woodiana* has also been shown in various aquatic environments (Beran, 2008; Lajtner and Crnčan, 2011). The reason for the current lack of native Unionids in the fishponds studied may be associated with their much lower tolerance of environmental conditions (Bielen *et al.*, 2016), a lower growth rate, and their lower reproductive potential (Blazek and Gelnar, 2006; Douda *et al.*, 2012; Reichard *et al.*, 2012). We are not able to state whether the lengths of dry periods have an impact on the occurrence of Chinese mussels, because of the lack of this type of data. According to Bódis *et al.* (2014a,b) fluctuations in the water level may also affect the mortality of alien and native mussels.

4.2 Density and biometric parameters of *S. woodiana* populations

In the Polish records that document the sites of occurrence of *S. woodiana*, the number of specimens collected and the morphological characteristics of shells and sometimes age are usually given (*e.g.* Andrzejewski *et al.*, 2013) while data about their density and biomass per unit area are rarely reported (Kraszewski and Zdanowski, 2001; Spyra *et al.*, 2012). The average density of *S. woodiana* in the Dębowiec pond complex was small and did not exceed 4 ind./m^2 except in pond 3. The factor limiting this species appearance is not the presence of macrophytes, whose well-developed root system makes it difficult for them to bury themselves, or due to a lack of preferred substrates (Kraszewski and Zdanowski, 2008–2010; Spyra *et al.*, 2012). All of the selected study sites were characterised by an absence of macrophytes (Paunović *et al.*, 2006; Demayo *et al.*, 2012). The occurrence of Chinese mussel is also not limited by the trophic character of the pond, which was confirmed by the presence of this species in alpine lakes (Cappelletti *et al.*, 2009; von Taurer, 2009; Ciutti *et al.*, 2011; Kamburska *et al.*, 2013). The reasons for its low density in the fishponds studied are probably a lack of their preferred, sandy substrate, and slow water flow, which in the opinion of Kraszewski and Zdanowski (2007) have a significant impact on its occurrence.

S. woodiana is known for the large morphological variability of its shells (Soroka and Zdanowski, 2001; Kraszewski, 2007; Guarneri *et al.*, 2014). The complex of fishponds studied is located in the same macro-physico-geographical region (Kondracki, 2002) as the ponds located near Goczałkowice (Spyra *et al.*, 2012). Both complexes are characterised by a similar kind of water supply, type of bottom sediments and management practice. An earlier study (Spyra *et al.*, 2012) showed that *S. woodiana* ranged from 19 to 225 mm in length. In this study the length of the mussels ranged from 42.4 to 213.8 mm, which confirms that this species has been present in Dębowiec fishponds for a long time. The maximum dimensions of shells in both complexes exceeded the sizes that were described for mussels from the warmest zone of the Konin lakes and were only slightly smaller than those that inhabit a zone of heated water discharge (241 mm) (Kraszewski and Zdanowski, 2007). In water environments of undisturbed thermal conditions in other regions of Europe, *S. woodiana* shells have reached 180 mm (Hungary) and even 250–270 mm (France) (Lajtner and Crnčan, 2011).

It appears that temperature influences the development of its larvae (Kamburska *et al.*, 2013), mussel density (Kraszewski and Zdanowski, 2007) and biomass, but has no effect on its life span. In the Konin lakes system the water temperature in winter does not fall below 7 °C and in summer it reaches 30 °C (Soroka and Zdanowski, 2001), which ensures the preferred thermal conditions described by Demayo *et al.* (2012). The research of Bódis *et al.* (2014a,b) indicates that the habitats with heated water can contribute to the aggregation and very large biomass of this thermophilic invasive species. This pattern was previously demonstrated in the Konin lakes where the biomass of mussels reached 27000 g/m^2 at a density of 68 ind./m^2. In cooler habitats, both lotic and lentic, that had a density of a few individuals per m^2 and different substrates, its biomass did not exceed 2000 g/m^2 (Kraszewski and Zdanowski, 2007). In the fishponds studied, Chinese pond mussel occurred in groups (except in pond 3) and only reached a relatively high biomass of up to 2951 g/m^2 at a density of 9 ind./m^2 (pond 1) and 2173 g at a density of 8 ind./m^2 (pond 2) on individual sites.

4.3 Age structure of populations of *S. woodiana* in fishponds

The age structure of the *S. woodiana* populations in Dębowiec was different from the ones found in heated Polish waters. Kraszewski and Zdanowski (2008–2010) showed that the largest group (70%) consisted of 3–5 years-old individuals whereas in our study the specimens were 7 and 8-year old (large). A few young and small (1 and 2-year old) and medium (4- to 5-year old) specimens occurred in one pond. Taking into account the age structure of the population studied it can be concluded with a high probability that the populations of *S. woodiana* remain in the regression stage in the Dębowiec fishponds. Although the presence of juveniles in pond 2 may indicate the possibility that the mussels are breeding, we are not able to exclude its re-introduction with fry. The carp fry, which is the main breeding fish, come from their own farms, but other species of fish are acquired from other fish farms. The thermal conditions of the ponds studied are typical of Central Europe, which makes this process a possible explanation (Douda *et al.*, 2012).

Nowadays, it is worth designing studies that are based on the size structure of the dead shells of *S. woodiana*, which can provide information on the variability in the age classes that are distinguished, especially due to the fact that dead shells provide shelter for other organisms for a long time after the death of the mussel (Schmidlin *et al.*, 2012). The increasing occurrence of this species in Polish freshwater environments will also allow further studies to be conducted on using *S. woodiana* as an indicator for monitoring purposes. These new research directions will become possible due to the documentation of new sites in which the Chinese pond mussel appears. Such directions will be worth exploring in the near future.

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